

High Power Lasers & Systems

by

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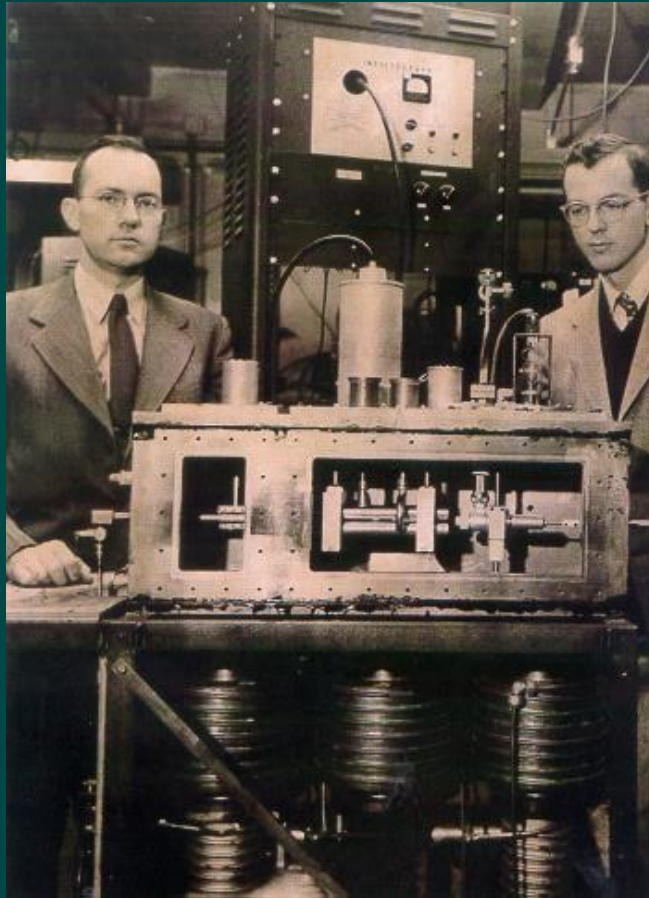
**IET Colloquium – Lecture Theatre AS3 – Richmond
Building, University of Sussex**

Brighton - 15th December 2015, 18:30

- Some laser history
- Airborne Laser Testbed & COIL
- Laser modes and beam propagation
- Fibre lasers and applications
- US Navy Laser system – NRL 33kW fibre laser
- Lockheed Martin 30kW fibre laser
- Conclusions

- 1917 - Albert Einstein developed the concept of stimulated emission, which is the phenomenon used in lasers
- In 1954 the MASER was the first device to use stimulated emission (Townes & Schawlow).
Microwave amplification by stimulated emission of radiation

Brief History of Lasers



Charles Townes & Jim Gordon at Columbia University
in 1954 with their second working MASER

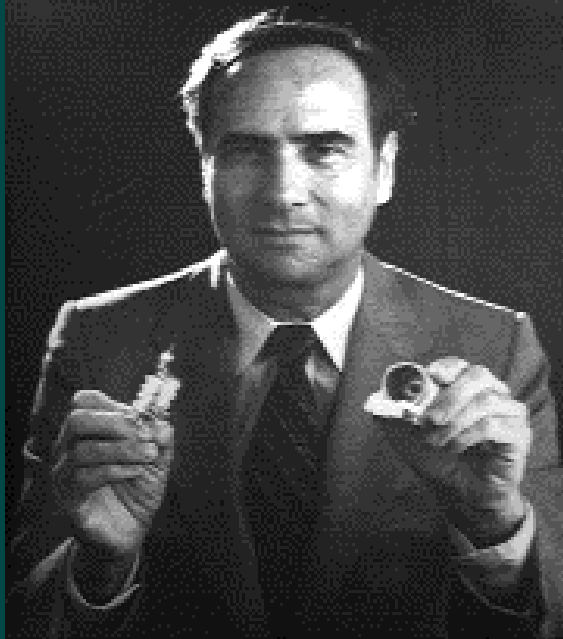
- In 1958 Townes & Schawlow suggested that stimulated emission could be used in the infrared and optical portions of the spectrum
- The device was originally termed the optical maser
- This term was dropped in favour of **LASER**. Standing for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

1st Laser - Ted Maiman 15th May 1960

- working alone and against the wishes of his boss at Hughes Research Laboratories

US

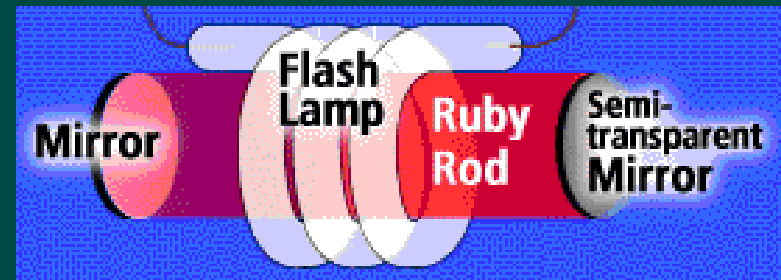
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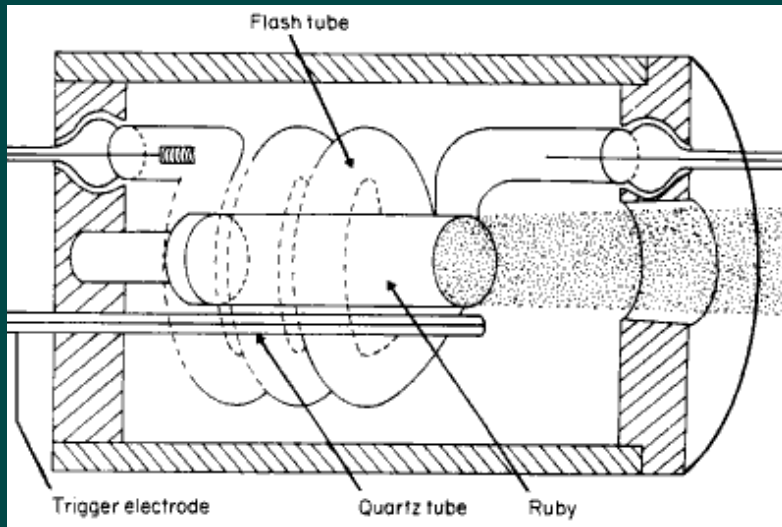
Electrical Engineer



Original Laboratory Set-Up for the Ruby Laser



Maiman's Ruby Laser - 694.3 nm

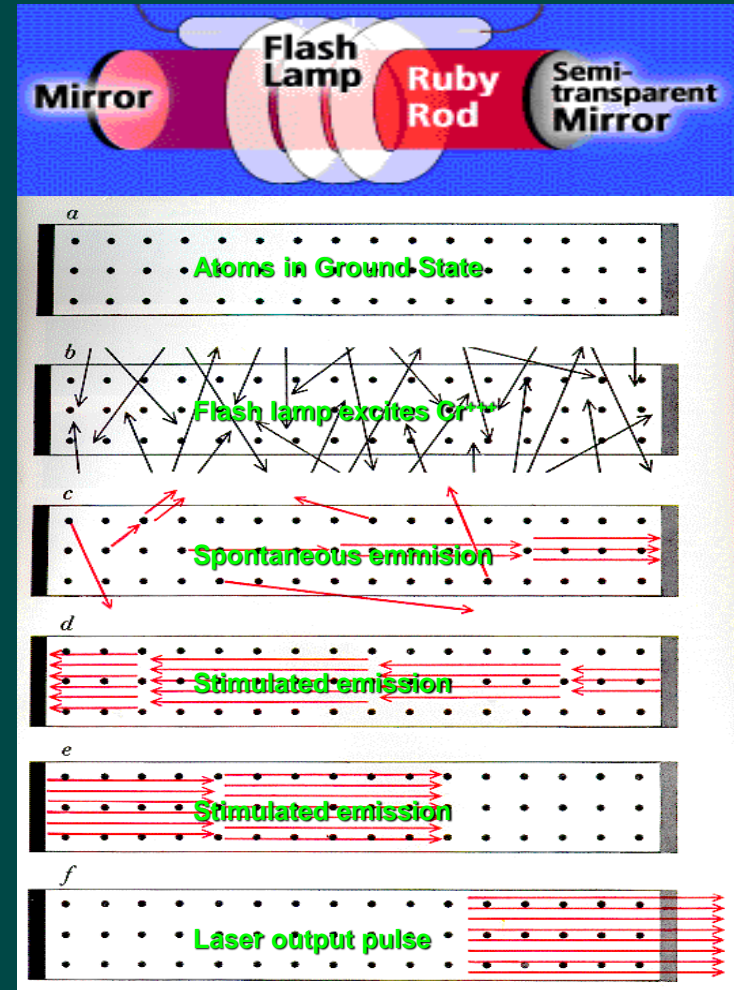
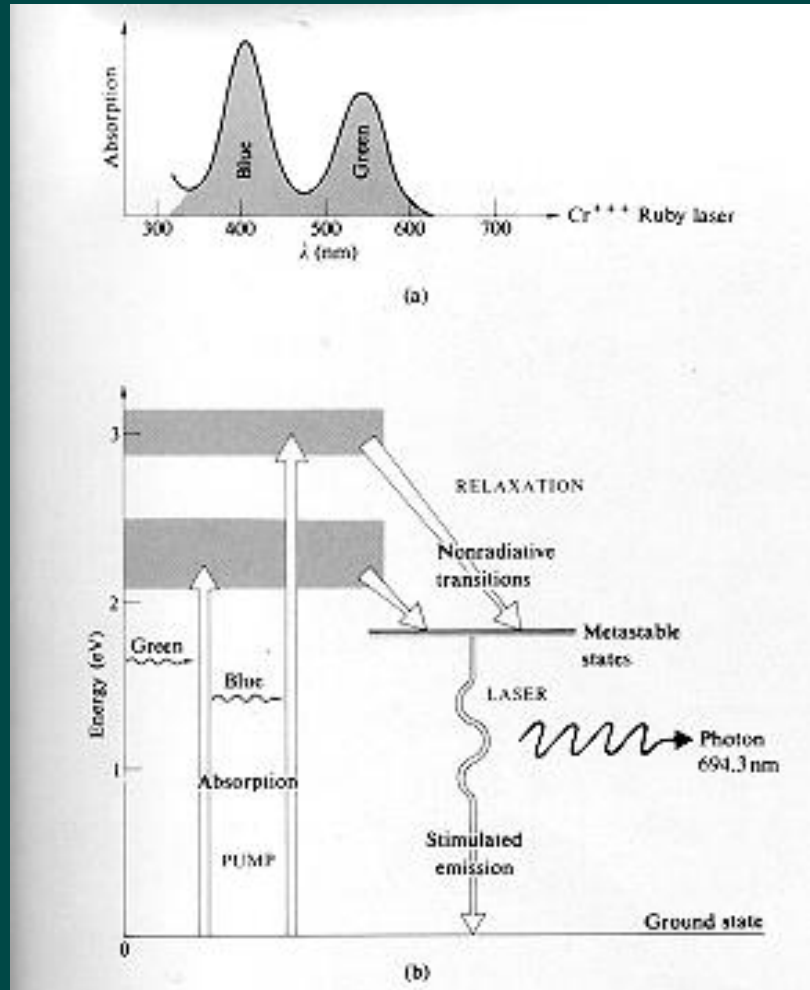


New York Times
8th July 1960,
Wrong Ruby Crystal
is shown here.
The journalist didn't
like the actual stubby
crystal. This crystal
was used later

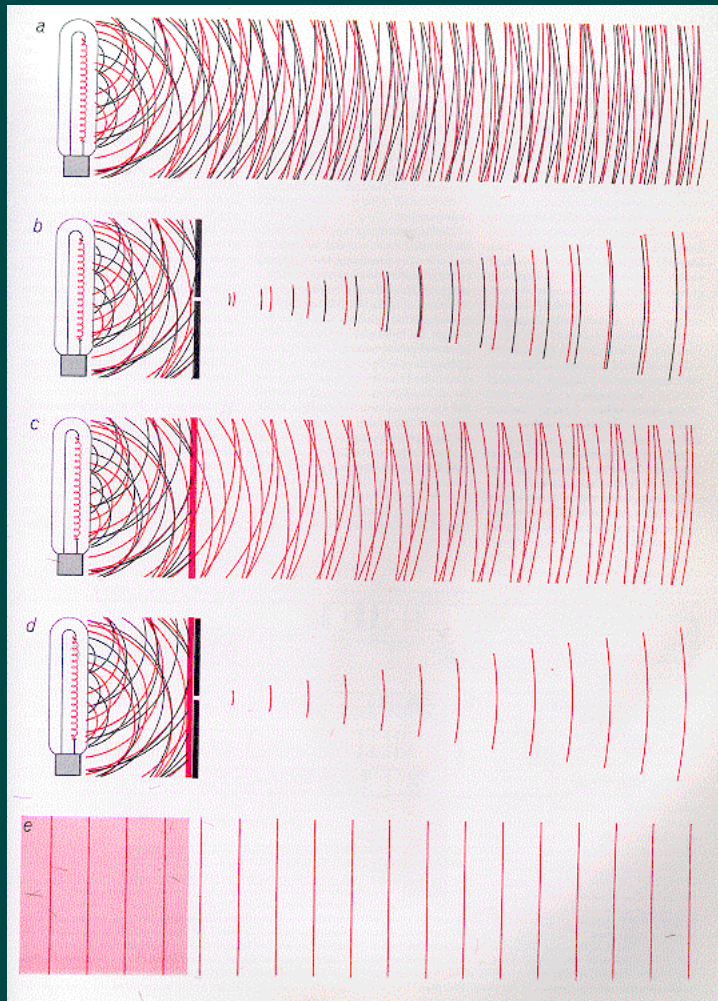


Synthetic pale pink ruby crystal Al_2O_3
containing about 0.05% by weight of Cr_2O_3

Stimulated Emission



Coherence and Focusing



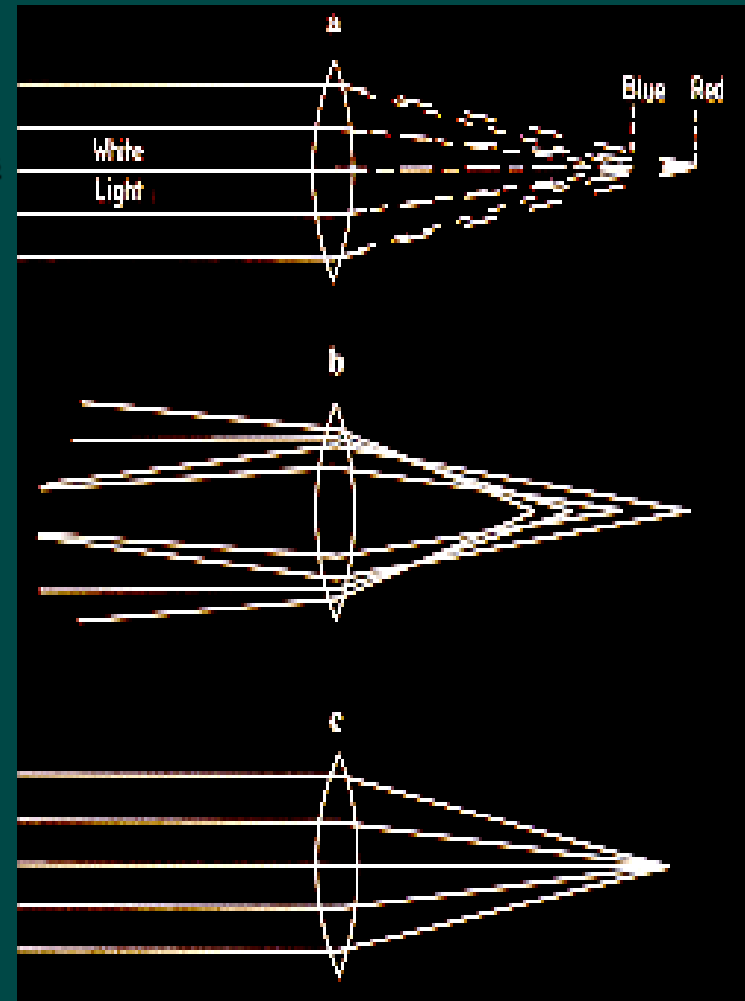
Spatially & temporally incoherent: out-of-step & various wavelengths

Spatially Coherent

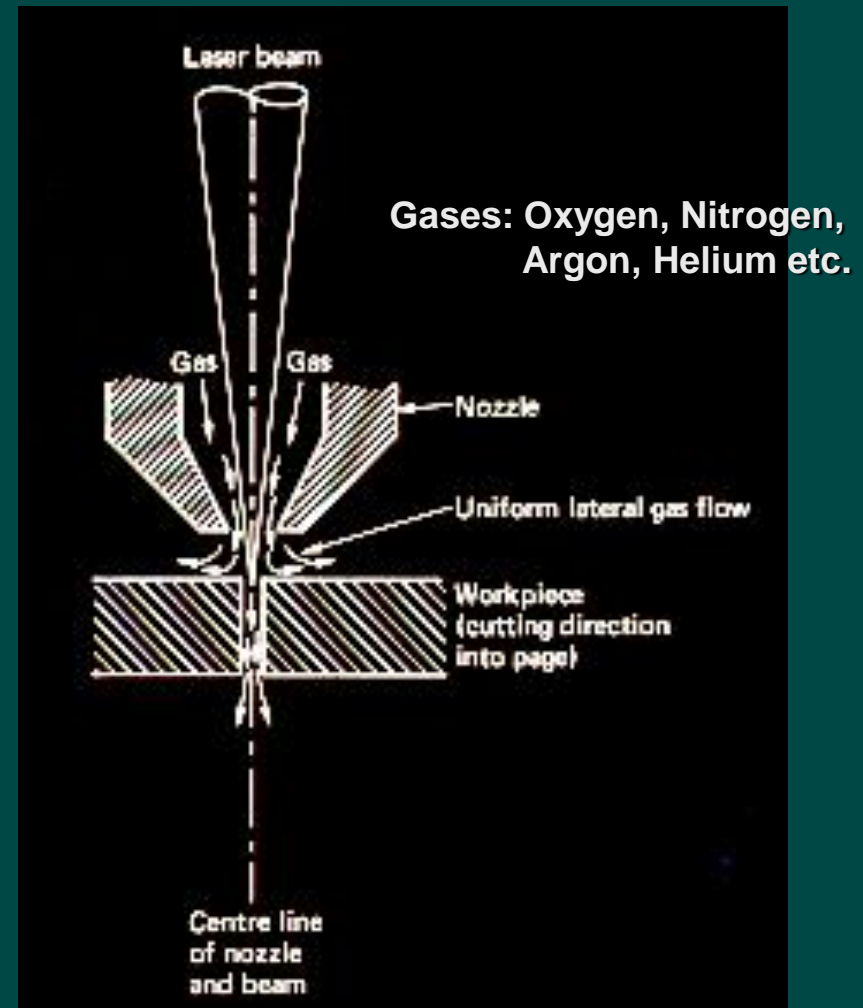
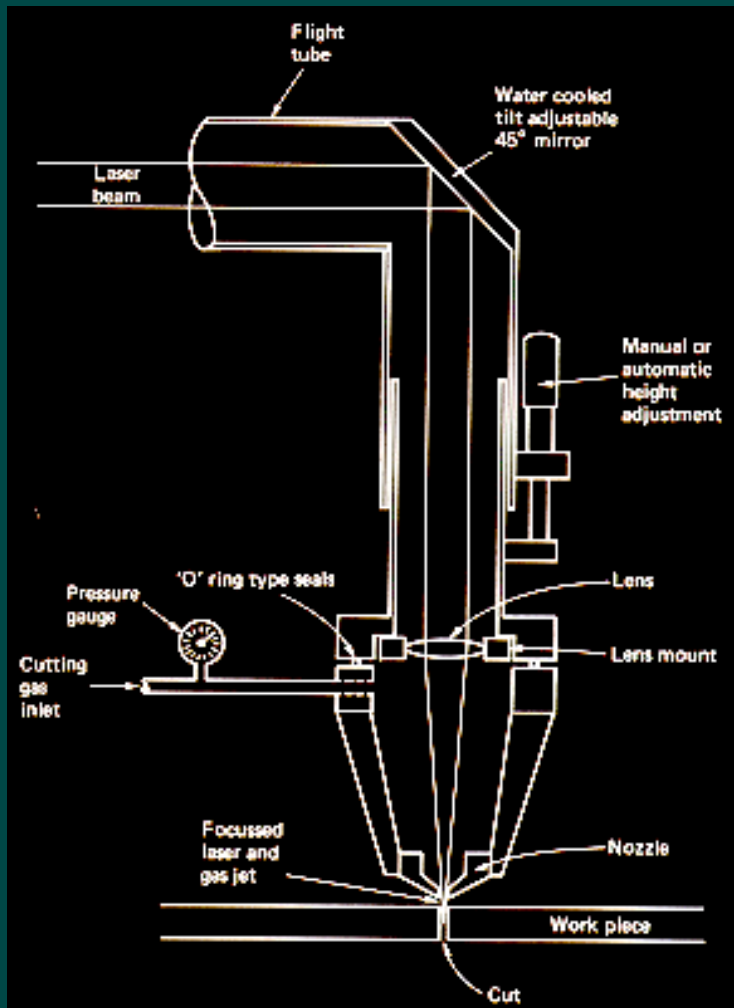
Temporally coherent single wavelength

Spatially & temporally coherent- only 1% left

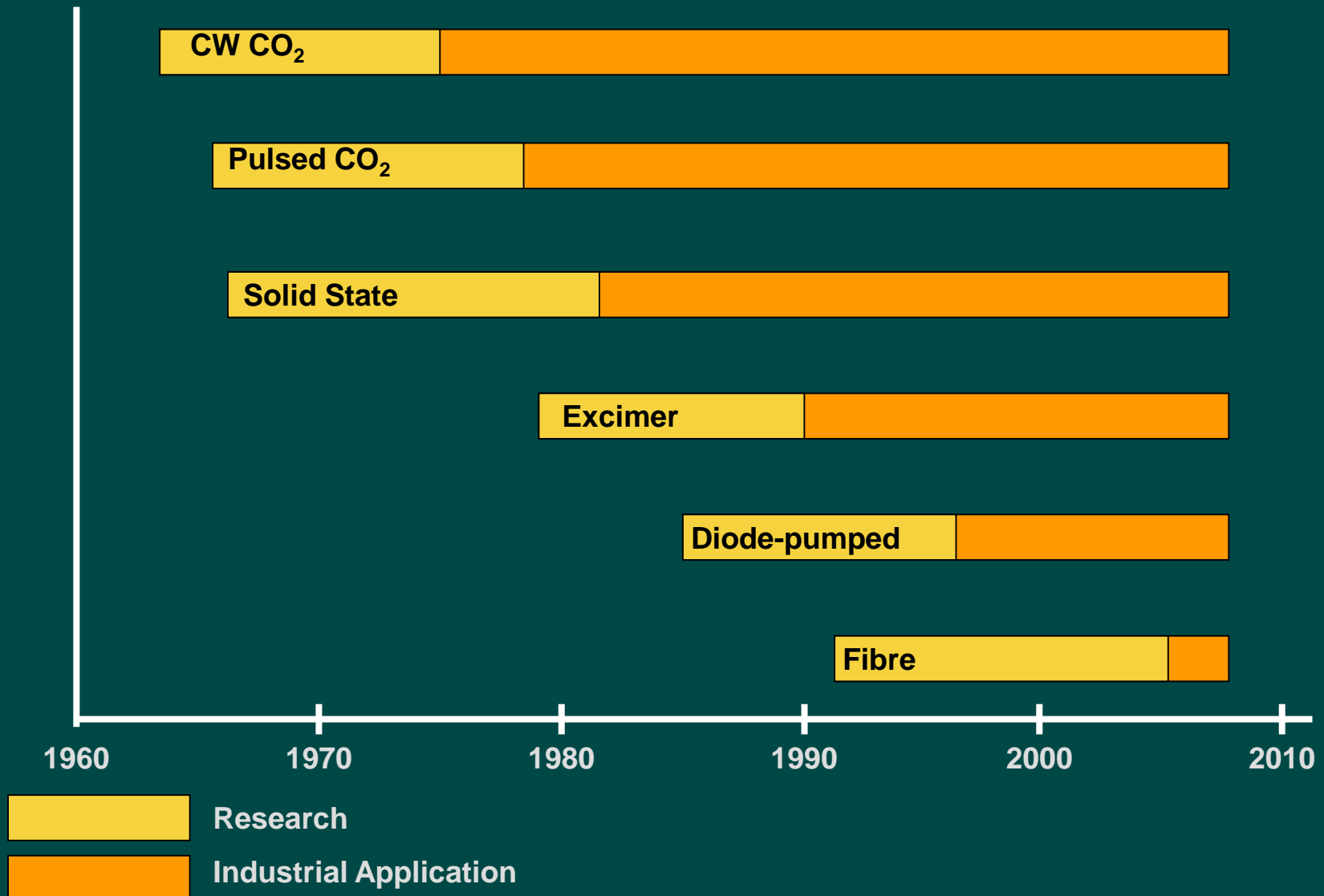
Laser Light 100% coherent



A Beam Focusing Lens and an Assist Gas Nozzle is required for all but UV lasers



Evolution of Industrial Lasers

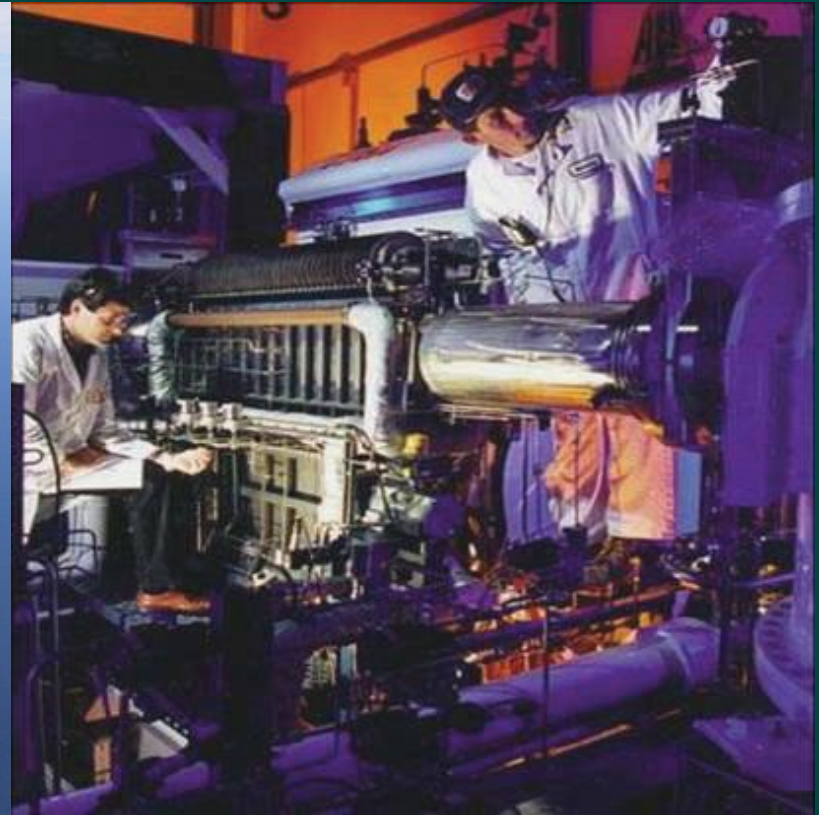


- Carbon Dioxide - up to 100kW more usually 2 to 7kW - $10.6\mu\text{m}$ ^[14,16]
- Nd-YAG - up to 4.5kW - $1.06\mu\text{m}$ - diode pumped^[17]
- Diode Lasers 2 kW
- Fibre Lasers 10kW single mode 50kW multimode >25% efficiency $1.064\mu\text{m}$
- Chemical oxygen iodine laser, or COIL, is an infrared chemical laser – wavelength $1.315\mu\text{m}$, a transition wavelength of atomic iodine

The Boeing YAL-1 Airborne Laser Testbed (ALTB)

- The **Boeing YAL-1** Airborne Laser Testbed weapons system was a megawatt-class chemical oxygen iodine laser (COIL) mounted inside a modified Boeing 747-400F.
- It is primarily designed as a missile defense system to destroy tactical ballistic missiles (TBMs), while in boost phase.
- Contractors: Boeing Defence (Aircraft), Northrop Grumman (COIL), Lockheed Martin (Nose turret and fire control system)

Megawatt Airborne Laser Test Bed (ALTB)

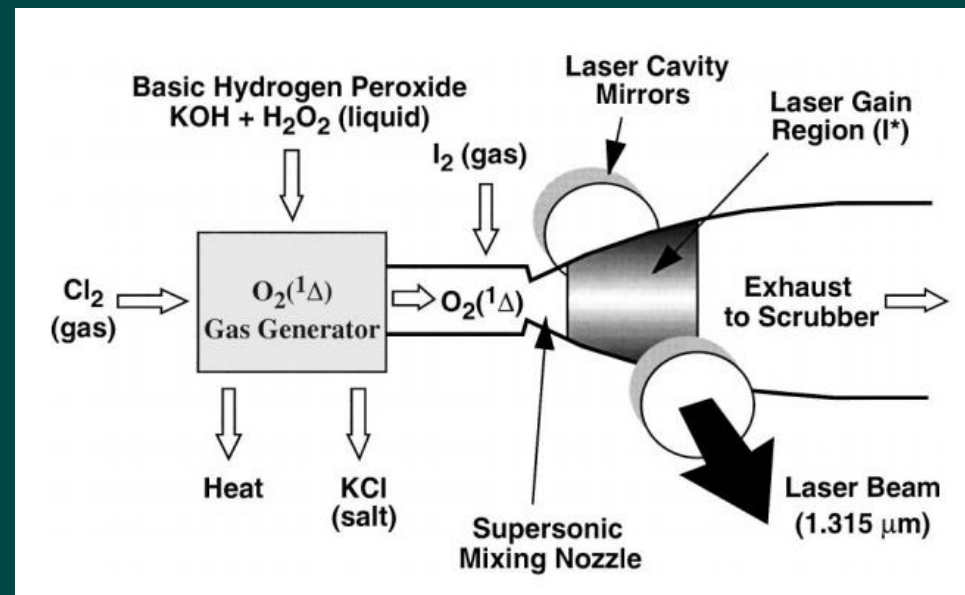


16 years of development and a cost of over \$5 billion

Amy Butler (December 21, 2011). "Lights Out For The Airborne Laser". Aviation Week

Chemical oxygen iodine laser (COIL)

- The laser is fed with gaseous chlorine, molecular iodine, and an aqueous mixture of hydrogen peroxide and potassium hydroxide.^[12]
- The excited oxygen has a spontaneous lifetime of about 45 minutes.
- This allows the singlet delta oxygen to transfer its energy to the iodine molecules injected to the gas stream; they are nearly resonant with the singlet oxygen, so the energy transfer during the collision of the particles is rapid.
- The excited iodine then undergoes stimulated emission and lases at $1.315\text{ }\mu\text{m}$ in the optical resonator region of the laser



Challenging resonator conditions
difficult to get a low M^2

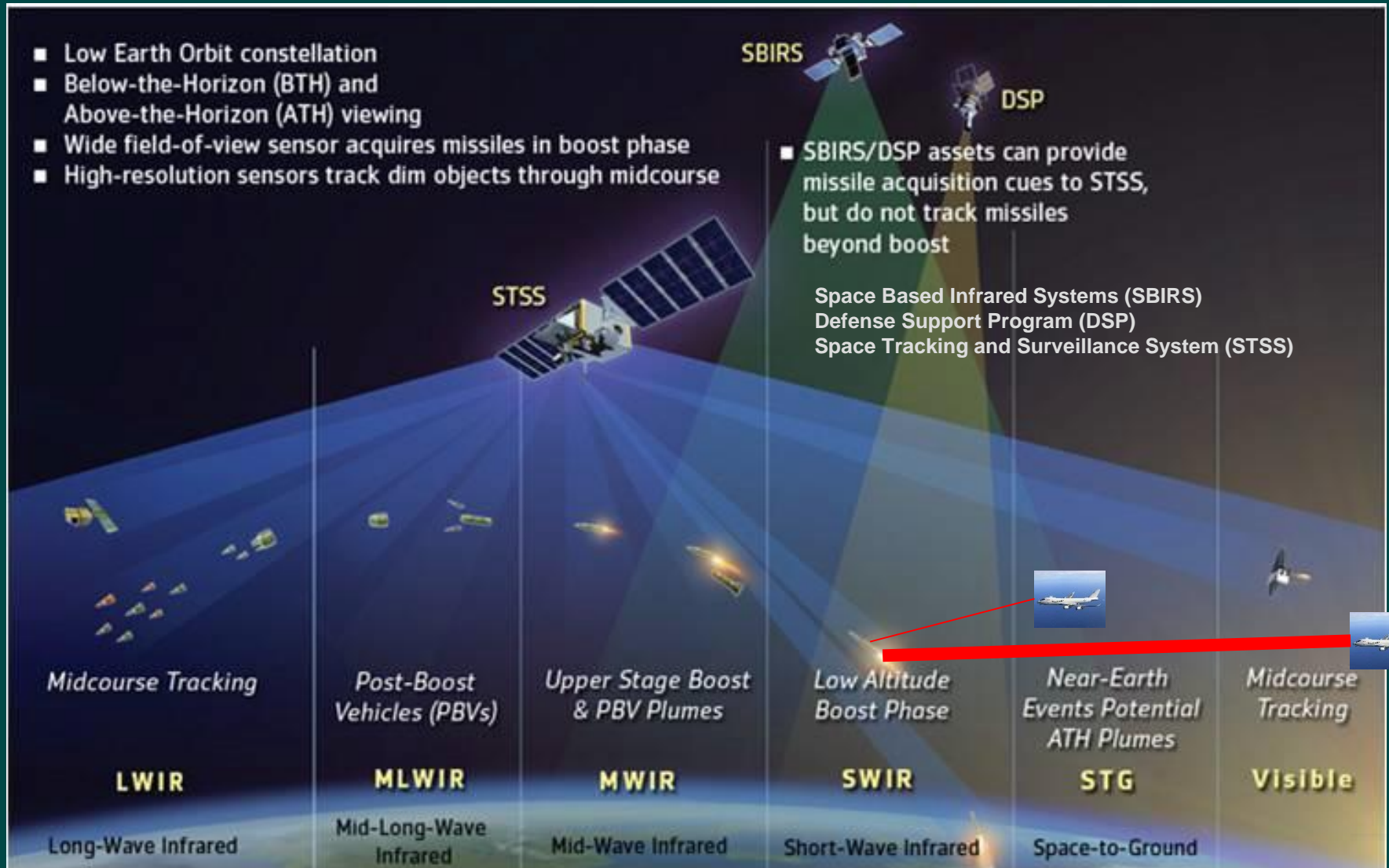
Chemical oxygen iodine laser (COIL) limitations



University of Sussex

- The heart of the system was the COIL, comprising six interconnected modules, each as large as an SUV. Each module weighed about 6,500 pounds (3,000 kg).
- Each 747 could carry enough laser fuel for about 20 shots.
- To refuel the laser, YAL-1 would have to land.
- To maintain a safe (700 km) firing distance from the launch site, it would need a laser something like 20 to 30 times more powerful than the chemical laser currently in the plane.
- The adventure in this project is commendable, only the USA could have completed this, I am sure many useful technologies were understood.

Integrated Detection Systems

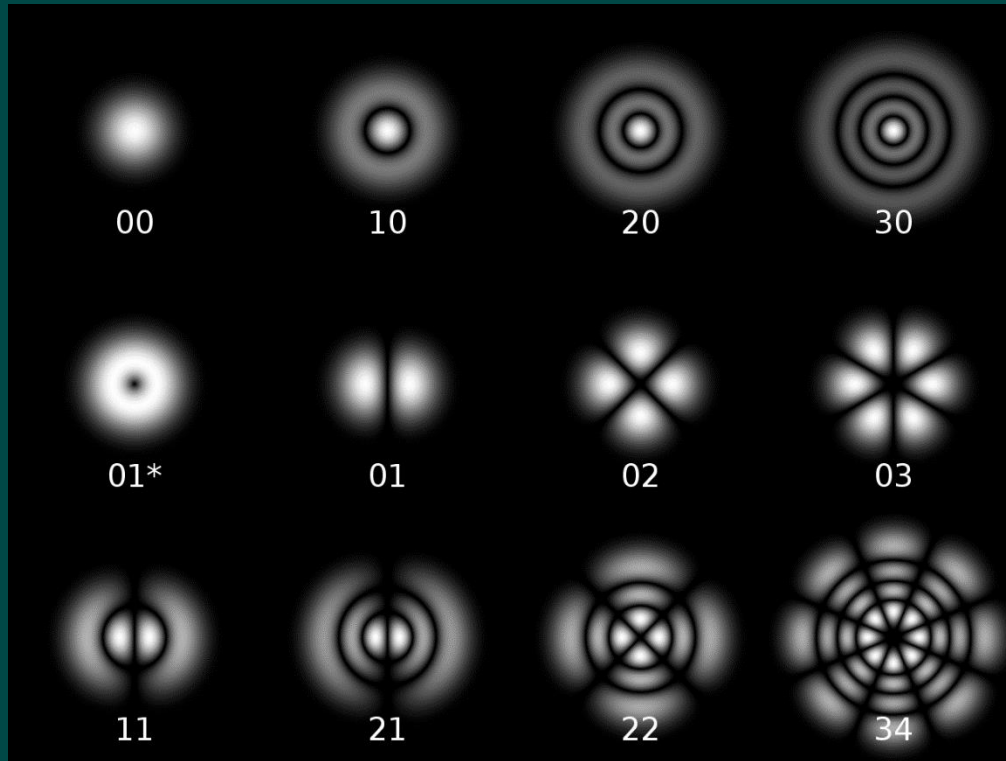


Rotatable beam delivery turret

- The main laser, located in a turret on the aircraft nose, could be fired for 3 to 5 seconds, causing a missile to break up in flight near its launch area.
- To be effective the ALTB would have had to have been within a few hundred kilometers of the missile launch point.
- On 12 February 2012, the YAL-1 flew its final flight, it was cancelled by defence secretary Robert Gates who said “to operationalise the system would require 10 to 20 747s, at a billion and a half dollars each, and a \$100 million a year to operate.”

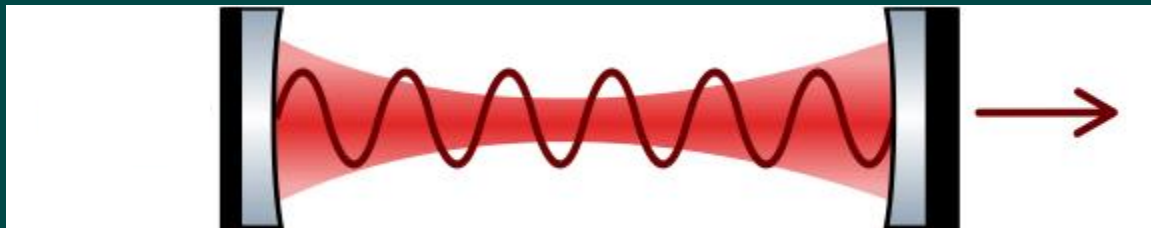


Laser Transverse Modes – cylindrical symmetry



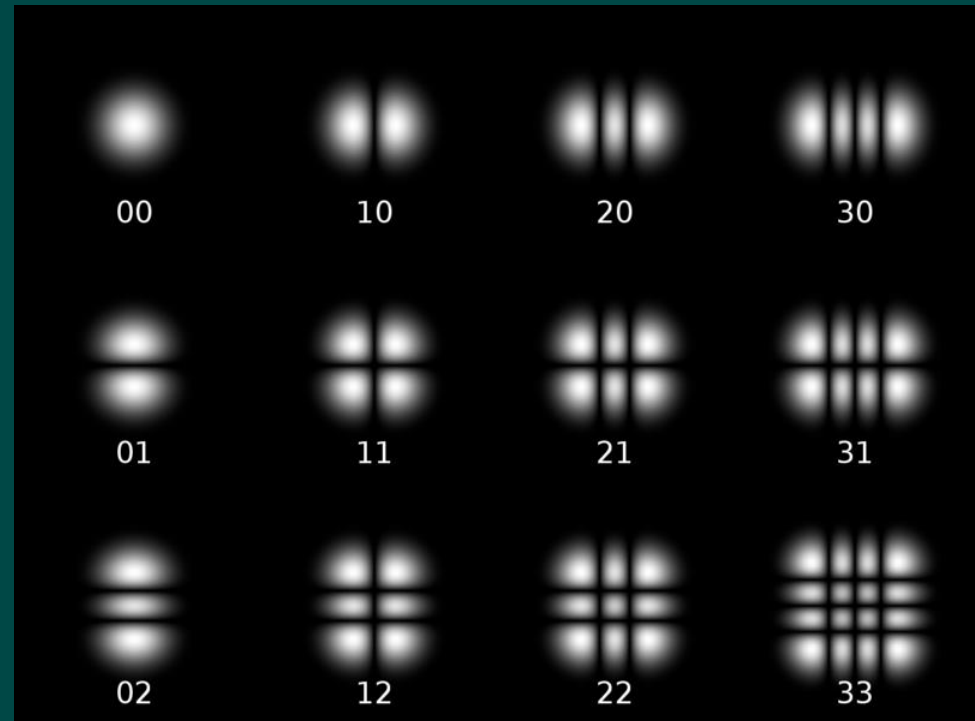
In a laser with cylindrical symmetry, the transverse mode patterns are described by a combination of a **Gaussian beam profile** with a **Laguerre polynomial**.

The modes are denoted TEM_pl where *p* and *l* are integers labelling the radial and angular mode orders, respectively.



Laser Transverse Modes – rectangular symmetry

- In many lasers, the symmetry of the optical resonator is restricted by polarizing elements such as **Brewster's angle windows**. In these lasers, transverse modes with rectangular symmetry are formed.
- These modes are designated TEM_{mn} with m and n being the horizontal and vertical orders of the pattern.



Transverse Modes in Fibres

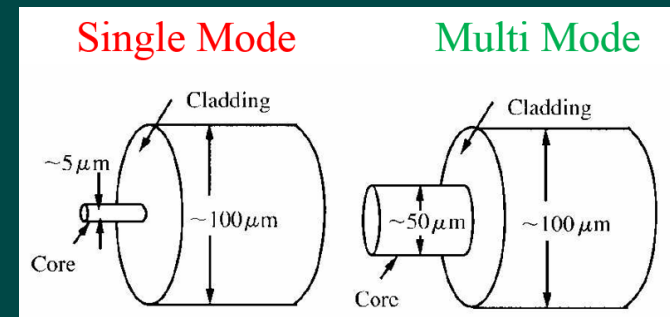
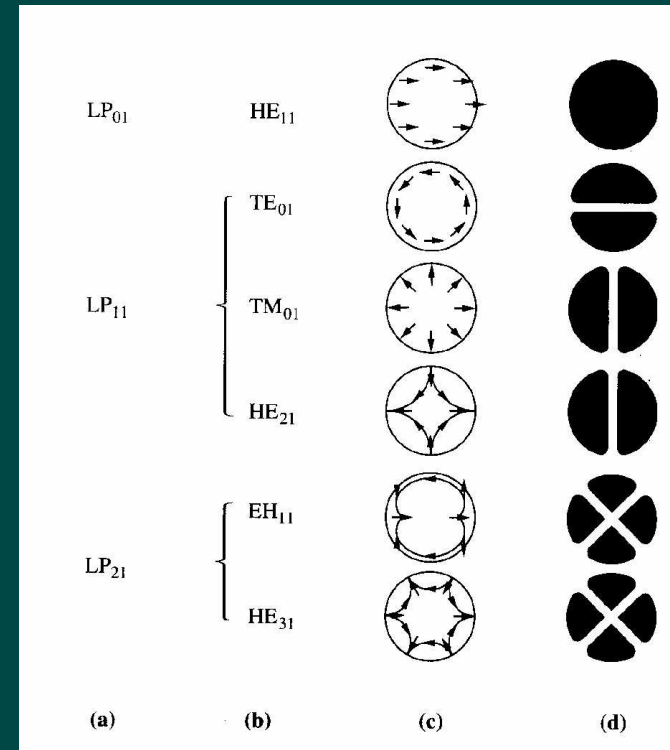
Some examples of low-order transverse modes of a step index fibre

(a) Linear polarized (LP) mode designations

(b) Exact mode designations

(c) Electric field distribution

(d) Intensity distribution of the electric field component



Beam waste, Rayleigh Range & Depth of Focus

For a Gaussian beam propagating in free space, the spot size $w(z)$ will be at a minimum value w_0 at one place along the beam axis, known as the beam waist .
For a beam of wavelength λ at a distance z along the beam from the beam waist, where the phase front is planar, the variation of the spot size is given by:

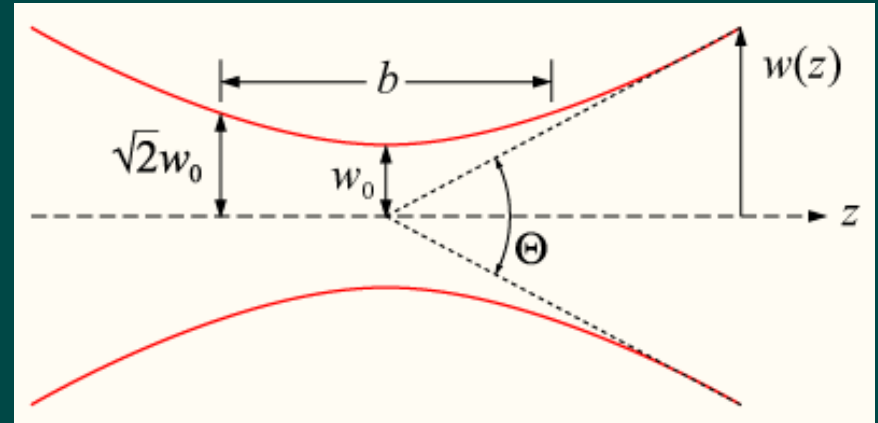
$$w(z) = w_0 \left\{ 1 + \left(\frac{z}{z_0} \right)^2 \right\}^{\frac{1}{2}}$$

$w(z)$ is the radial distance at which the field amplitude drops to $1/e$ of its value on the axis and the power density is decreased to $1/e^2$ of its axial value

where the origin of the z -axis is defined, without loss of generality, to coincide with the beam waist, and where

$$z_0 = \frac{\pi w_0^2}{\lambda}$$

Is called the Rayleigh range



At a distance from the waist equal to the Rayleigh range z_0 , the width w of the beam is

$$w(\pm z_0) = w_0 \sqrt{2}$$

The distance between these two points is called the confocal parameter or **depth of focus** of the beam:

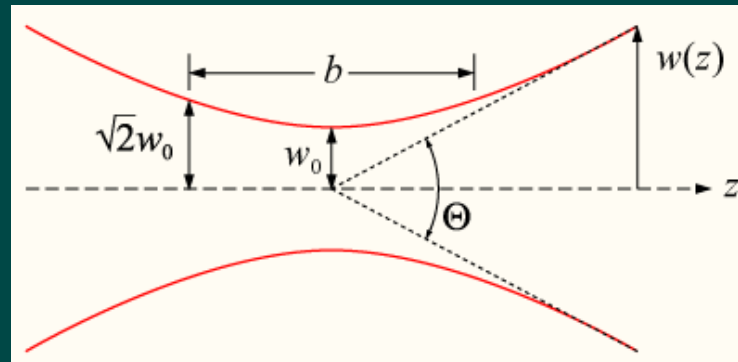
$$b = 2z_0 = \frac{2\pi w_0^2}{\lambda}$$

Angular Spread of the Beam

The parameter $w(z)$ approaches a straight line for $z \gg z_0$. The angle between this straight line and the central axis of the beam is called the divergence of the beam. It is given by

$$\theta \cong \frac{\lambda}{\pi w_0} \quad (\theta \text{ in radians})$$

The total angular spread of the beam far from the waist is then given by $\Theta = 2\theta$

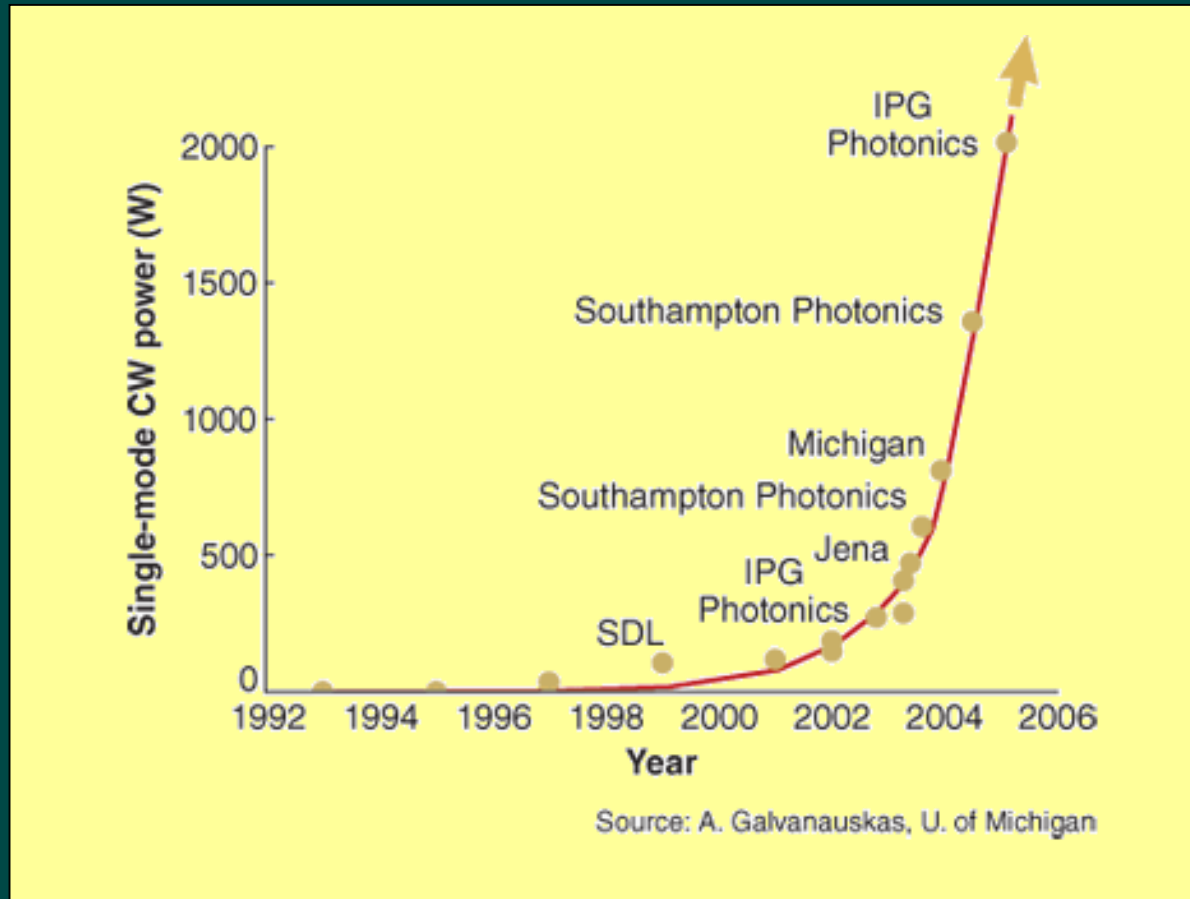


Because of this property, a Gaussian laser beam that is focused to a small spot spreads out rapidly as it propagates away from that spot. To keep a laser beam very well collimated, it must have a large diameter.

- The M^2 factor, also called *beam quality factor* or *beam propagation factor*, is a common measure for the beam quality of a laser beam.
- The beam divergence is: $\theta = M^2 \lambda / \pi w_0$, in my opinion this was the problem for the COIL system
- where w_0 is the beam radius at the beam waist and λ the wavelength. A laser beam is often said to be " M^2 times diffraction-limited". A diffraction-limited beam has an M^2 of 1, and is a Gaussian beam. Smaller values of M^2 are physically not possible.

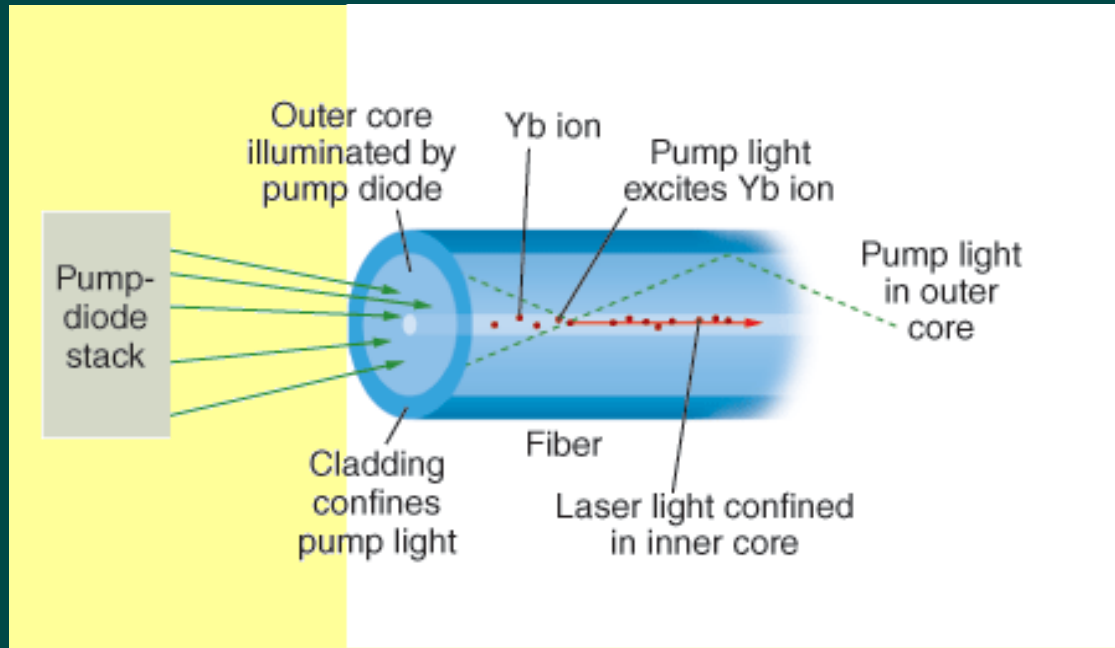
- The M^2 factor of a laser beam limits the degree to which the beam can be focused for a given beam divergence angle, which is often limited by the numerical aperture of the focusing lens.
- Together with the optical power, the beam quality factor determines the **brightness** (more precisely, the radiance) of a laser beam.

High Power Fibre Lasers



The steady march of high-power single-mode output from ytterbium-doped fibre lasers is continuing.

Fibre Laser Operation



Pump light from a diode-laser stack illuminates the outer core of a dual-core fiber (focusing optics are not shown for simplicity).

The cladding confines the pump light in the outer core so it passes through the inner core.

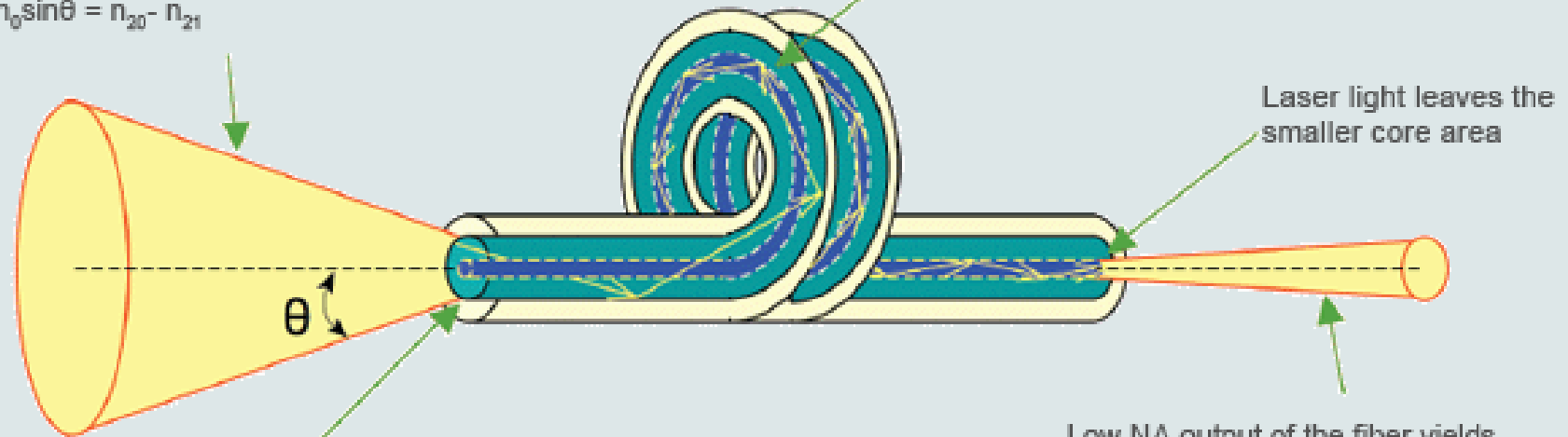
One pump photon excites an ytterbium atom in the inner core, which emits light that is confined in the inner core, becoming part of the fiber-laser beam

How a Fiber Laser/Amplifier Works

The angle, θ , at which light is accepted is determined by the numerical aperture (NA) which is dependent upon the refractive indices of the fiber clads, n_0 and n_1

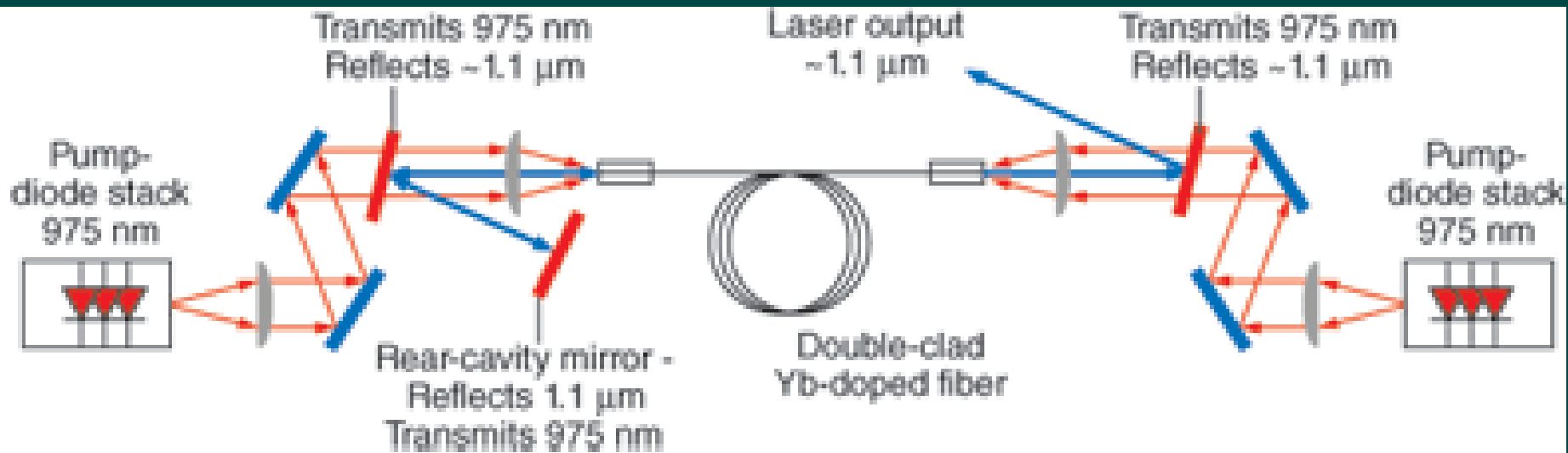
$$NA = n_0 \sin \theta = n_{20} - n_{21}$$

Pump light is absorbed by a rare earth ion in the core and converted into laser light; coiling is used to suppress higher order modes



The high NA input of the double clad structure provides a broad acceptance angle for low brightness pump energy to enter the large pump clad

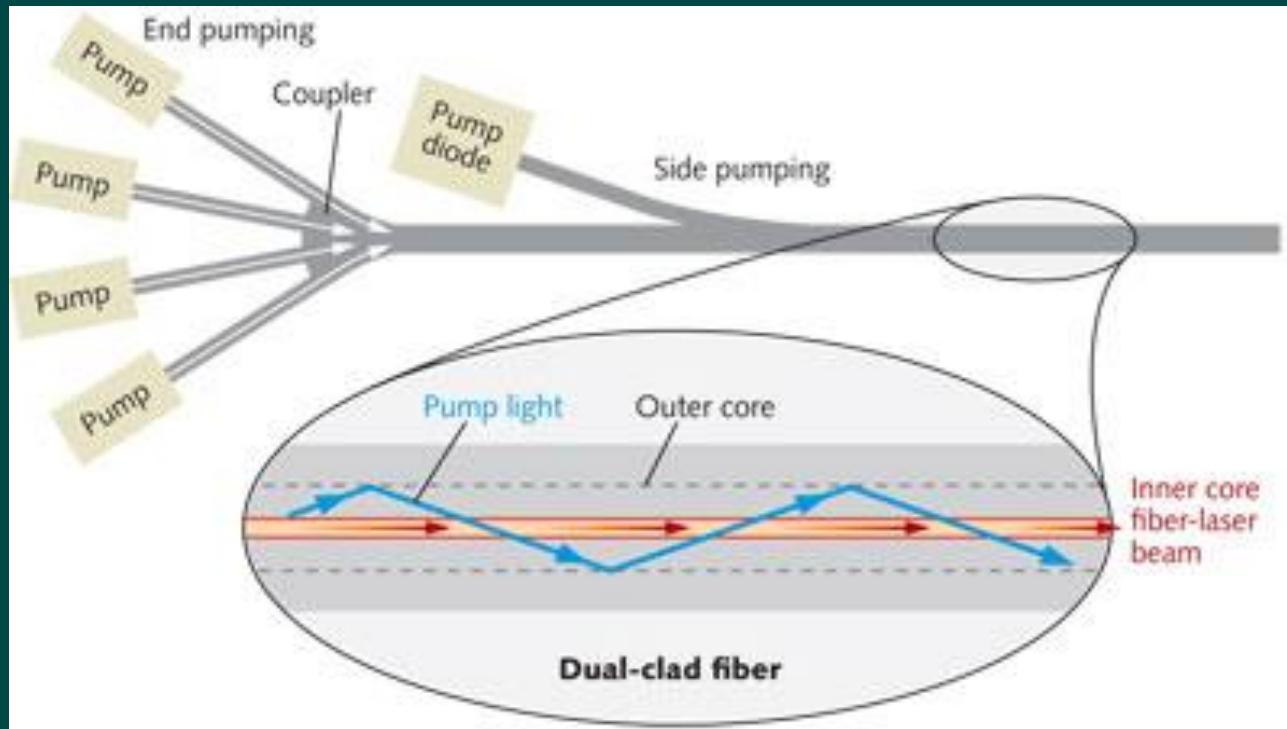
Low NA output of the fiber yields a high brightness, low divergence, single mode beam



A high-power Yb-doped fiber laser is pumped from both ends. Filters transmit the 975-nm pump light into the laser cavity while serving as mirrors that reflect the 1.1- μm laser light.

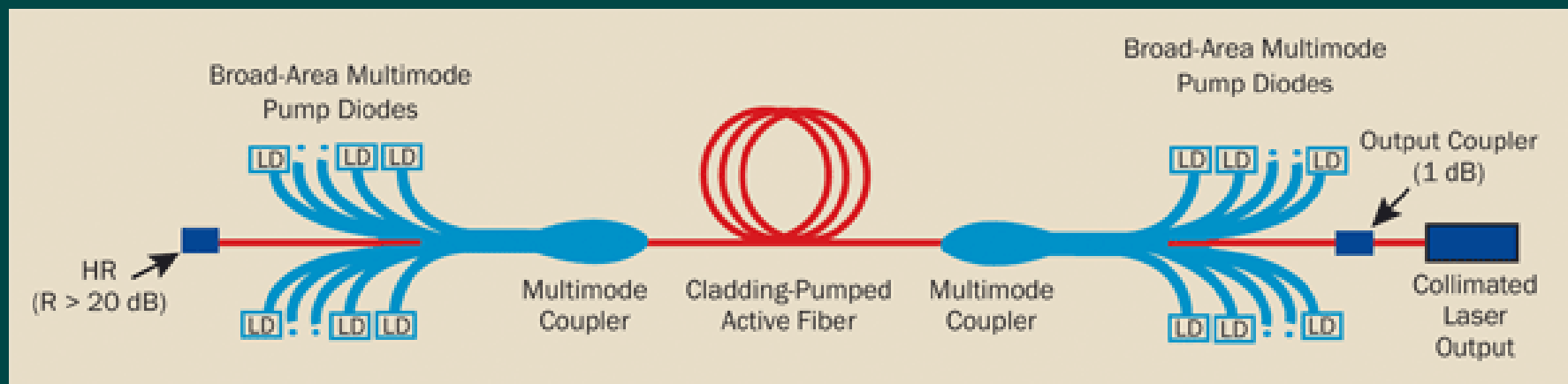
This is a simplified version of the arrangement that generated 1.3 kW CW in experiments at Southampton.

- A fiber laser can be end-pumped with one or many lasers, or side-pumped (usually with many lasers) by side-coupling pump light into the outer core.



A typical single-mode fibre laser utilizing single-emitter diodes

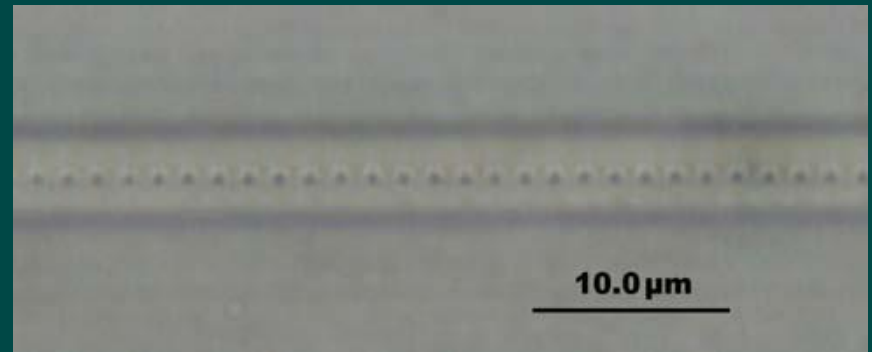
- The emission wavelength is a function of choices in the doped fibre and the type of reflector - a typical example would be Bragg gratings.
- This single-mode core is typically 5 to 12 μm in diameter. The double-clad fibre consists of an inner single-mode core doped with the appropriate rare-earth ions such as: neodymium, erbium, ytterbium and thulium.



Fibre lasers are available up to 50 kW in power from IPG Photonics



<http://www.youtube.com/watch?v=LVpD5y7ngA4>



Optical microscope image of the core of a Ytterbium doped fibre laser showing the individually inscribed grating periods of a grating for operation at 1064 nm.

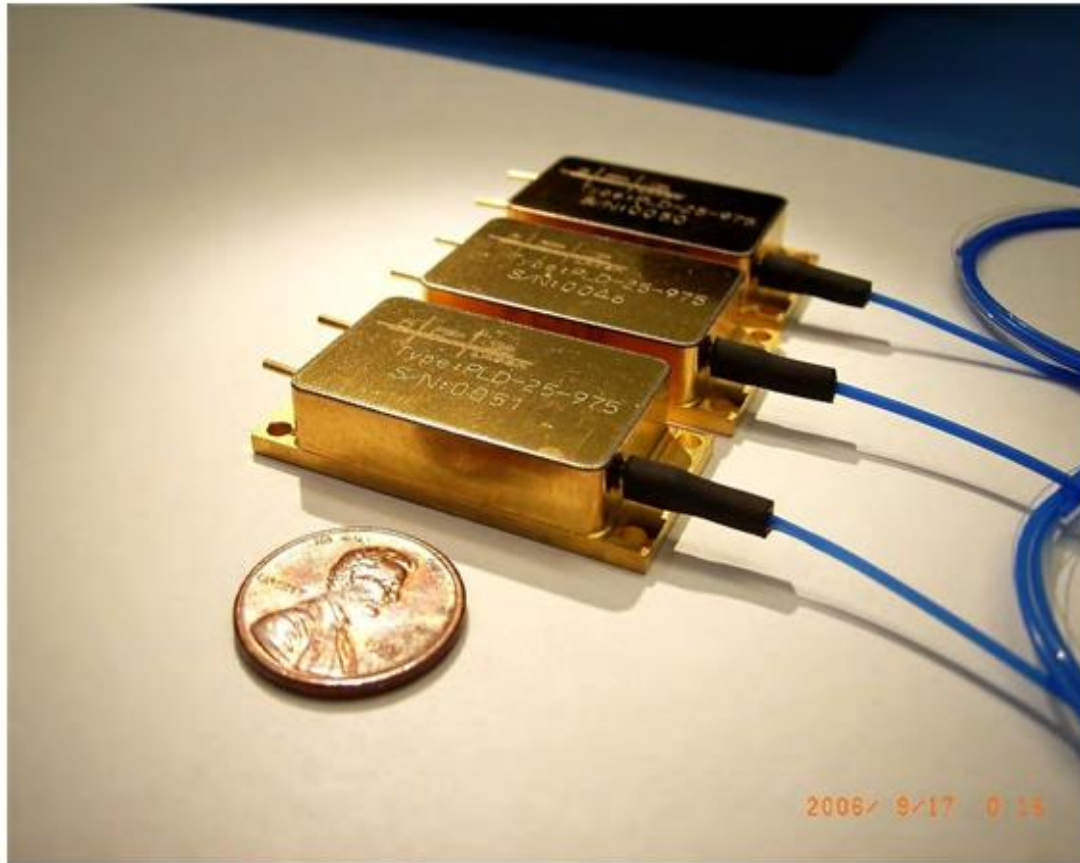
Courtesy: Graham D. Marshall et al

Single mode operation is vital

- The highest single-mode power available from a fiber laser is 10 kW, from IPG Photonics, single mode $M^2 \sim 1$
- Hence near diffraction limited performance
- The IPG system, has a master oscillator that produces a kilowatt of optical power that is fed into an amplifier stage pumped at 1018 nm with light from other fibre lasers.
- IPG single mode fibre lasers have a Mode Field Diameter of $\sim 15 \mu\text{m}$
- Due to the high efficiency of these lasers $\sim 30\%$, these lasers have modest water cooling requirements
- The entire laser system is about the size of two refrigerators.

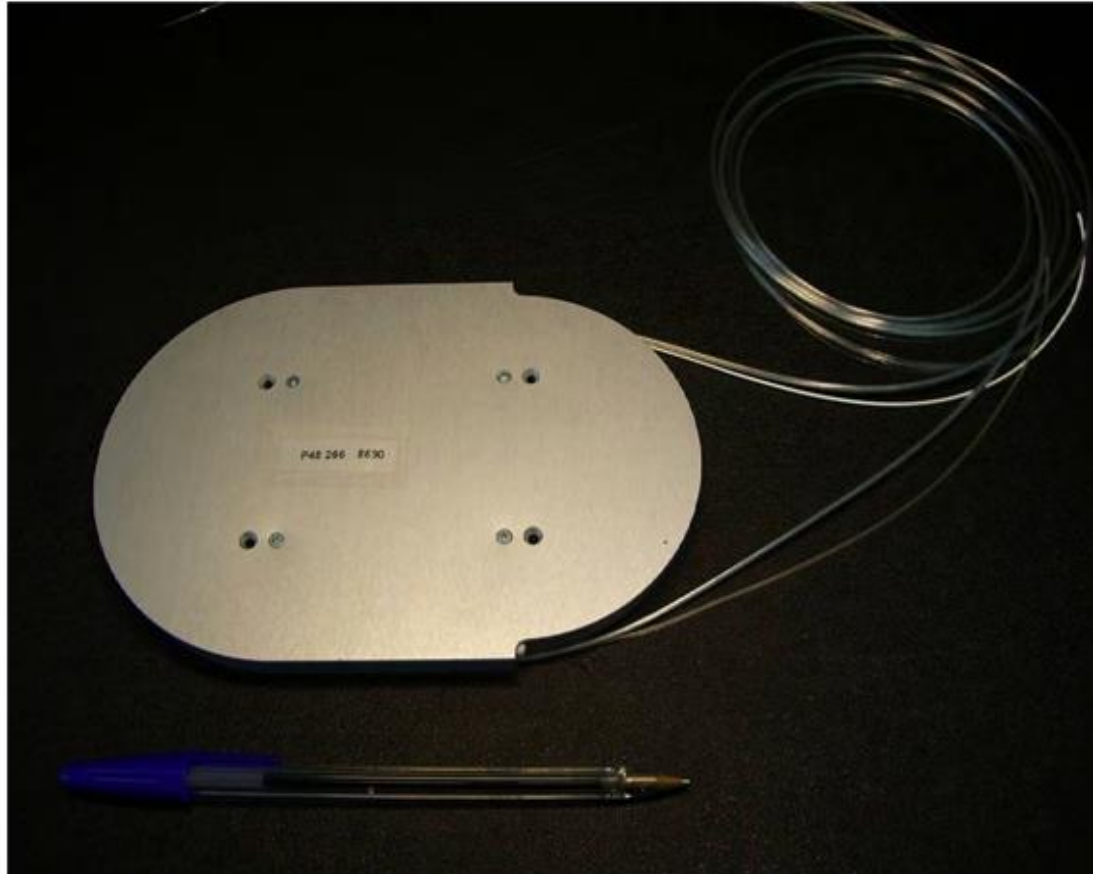
- The highest multimode power reached is 50 kW, also by IPG Photonics.
- The system relies on incoherent beam combination, so it's not a super high-quality beam (beam parameter product of 10, M^2 of 33).
- Lasers with large values of M^2 have limited effective range due to the large diffraction spreading angle:
$$\theta = M^2 \lambda / \pi \omega_0$$

25W Pump Diode Modules - IPG

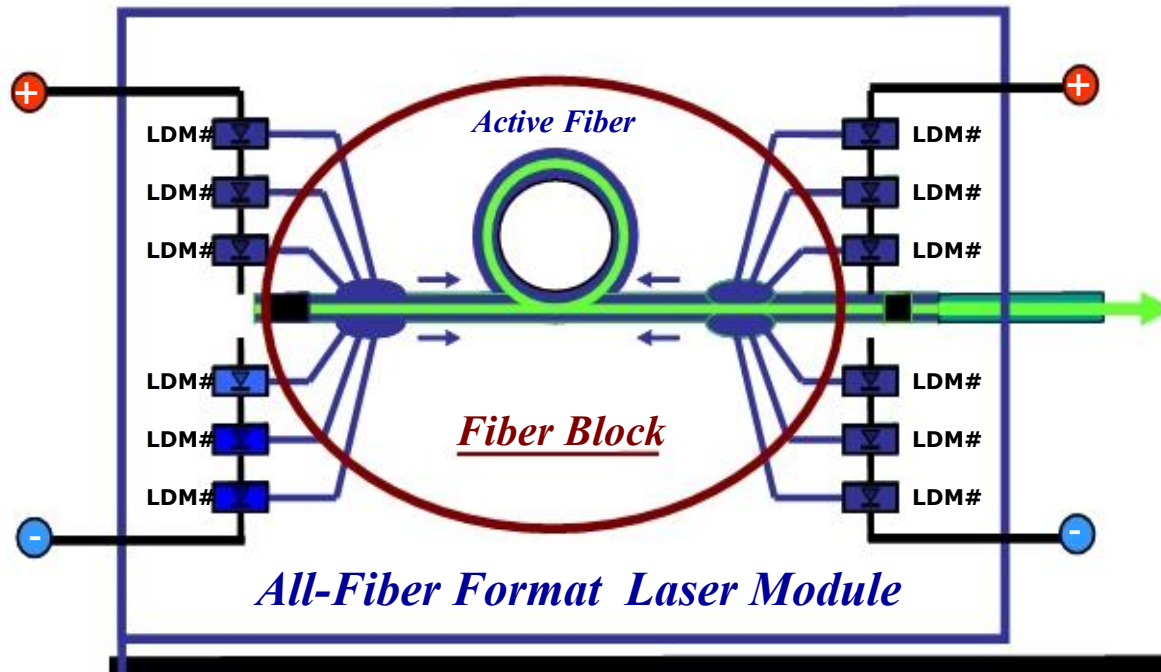


<https://www.youtube.com/watch?v=ofEqFlqkiS0> fibre laser operation

400W...700 W Ytterbium Fiber Blocks - IPG



IPG Conception - IPG

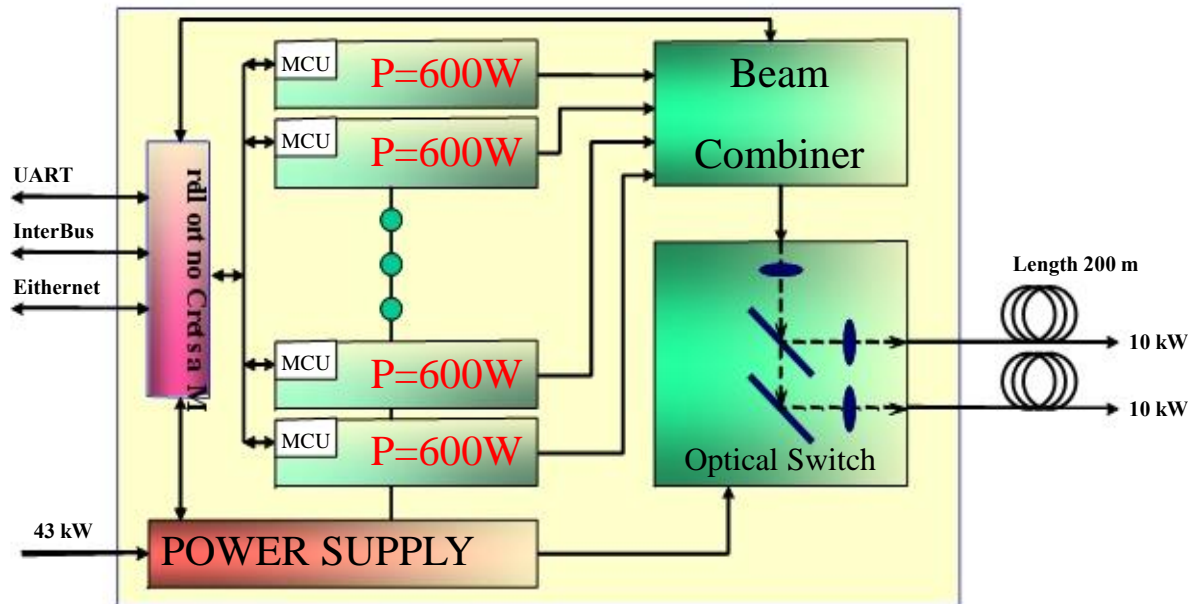


Compact integrated optical design

- In parallel combining by single emitter diodes
- Side pumping
- Robust mechanical construction

kW-(multimode)-Fiber Lasers - IPG

YLR-10000: Block Diagram

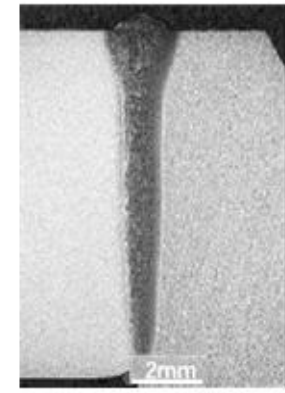
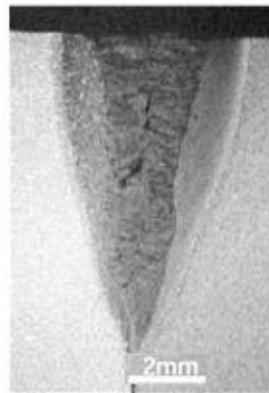




Welding of Gear Box Parts

CO₂-Laser *Electron beam*

Fiber Laser

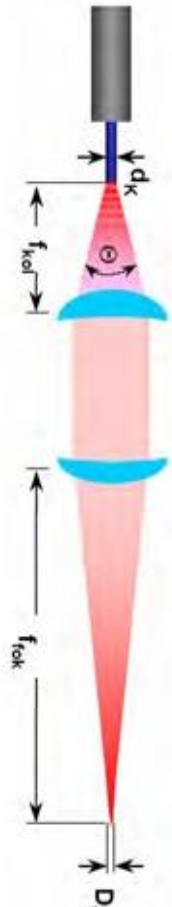


- Low heat input; Low distortion
- Reduced crack risk

YLR4000-S

<http://www.youtube.com/watch?NR=1&v=8B35zeYmeO4&feature=endscreen> fibre laser cutting

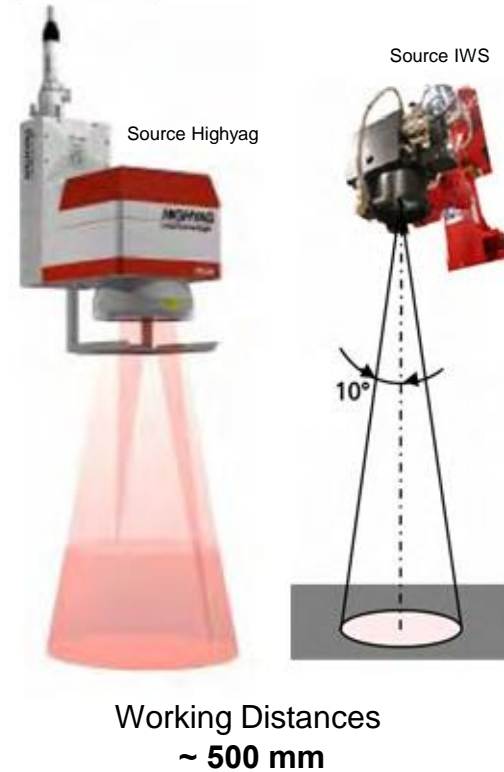
Fiber Laser Remote Welding - IPG



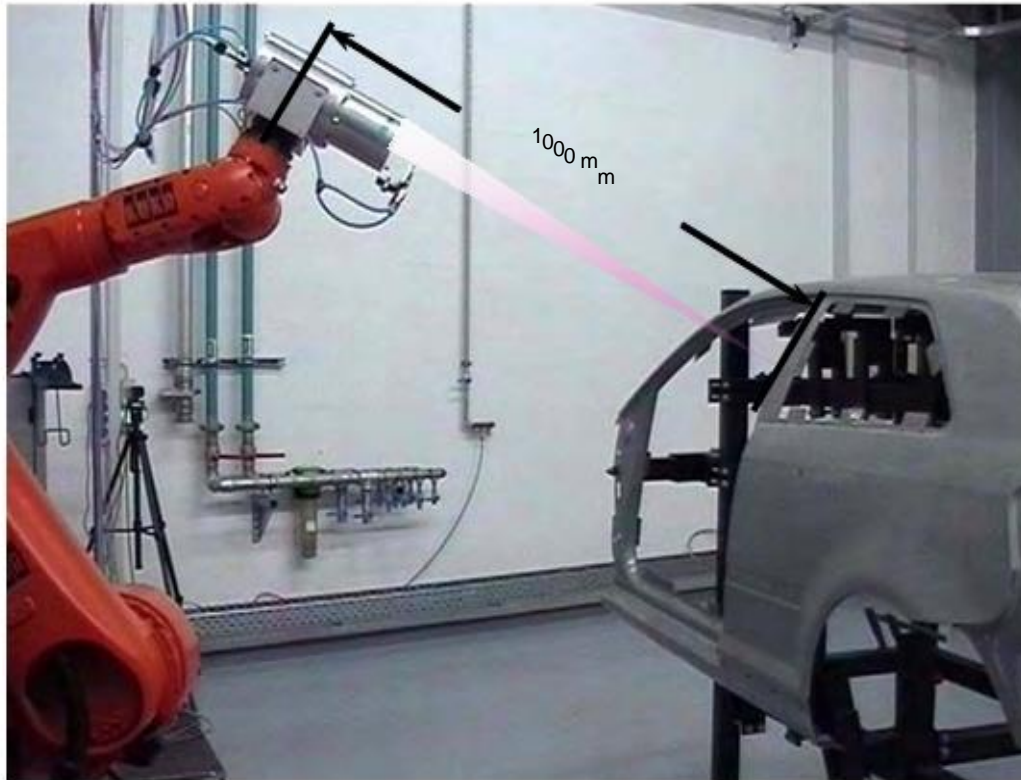
Scannerfree Remote Processing



Scanner Remote Processing



Remote Welding of Body in White (BIW)



High productive stitch welding for body in white

Fibre lasers replacing CO₂ lasers



Fanuc welding robot using fibre laser – 50kW lasers are available



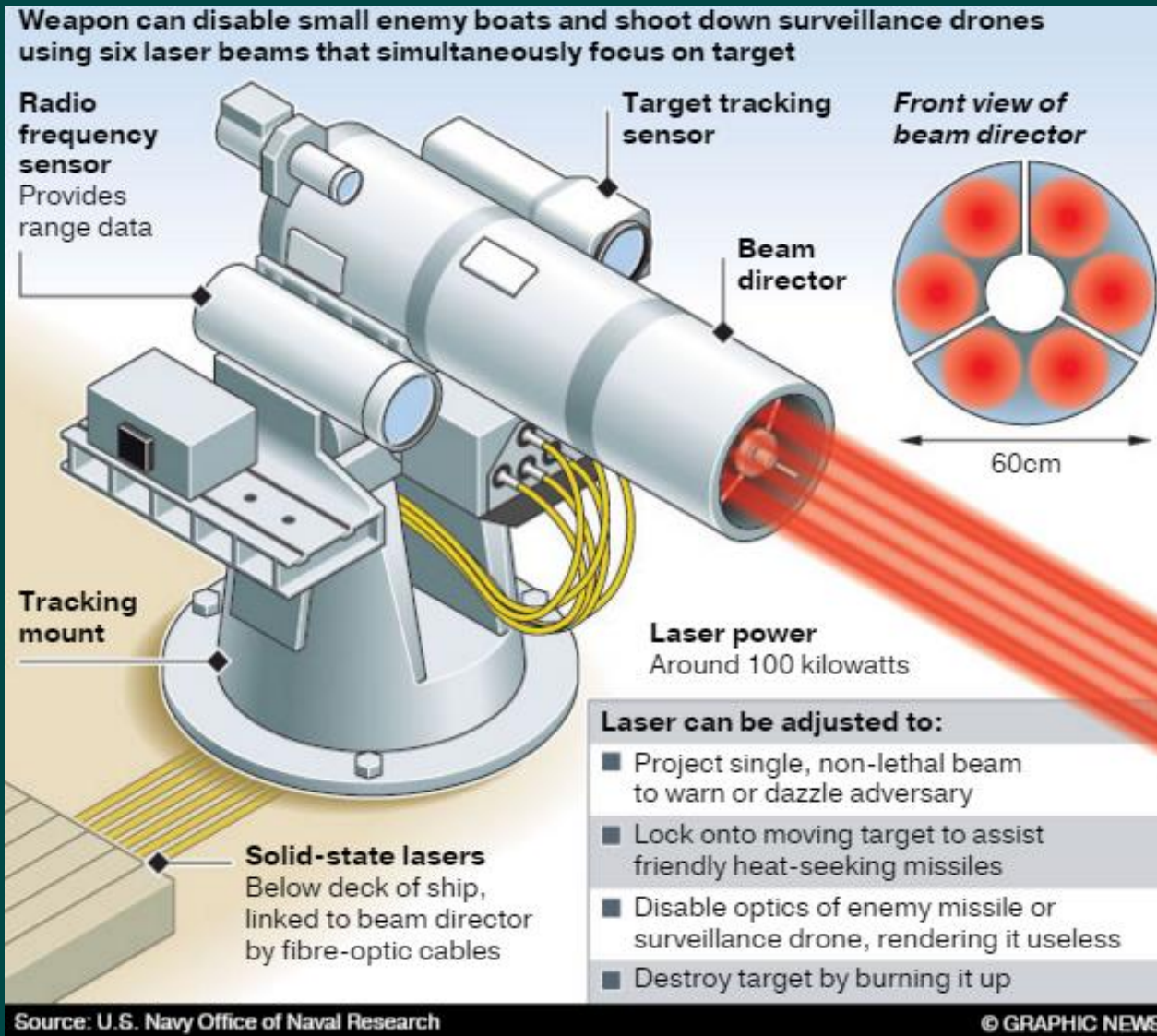
US Navy Laser Weapon System (LaWS) - NRL

- The US Navy's Laser Weapon System (LaWS) contains six individual fiber lasers with their beams incoherently combined into a single 33 kW output. (*Courtesy of US Navy*)



<http://www.laserfocusworld.com/articles/print/volume-48/issue-04/features/the-state-of-the-art.html>

US Navy Laser Weapon System (LaWS)



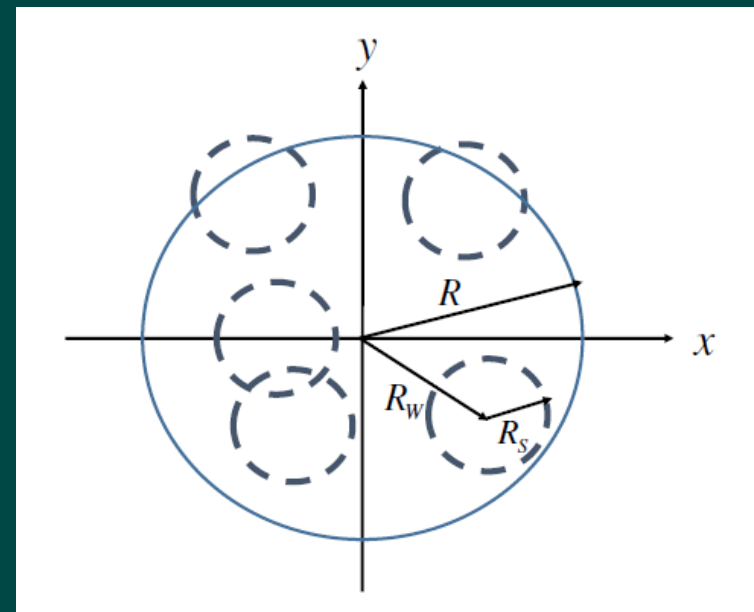
US Navy Laser Weapon System (LaWS)



- Absorption/scattering
 - i. Molecules, Atoms and Aerosols scatter the beam. This can be minimised by operating at a wavelength of $1.045\mu\text{m}$*
 - ii. At high powers heating of the medium causes thermal blooming*
- Thermal blooming
 - i. The absorbed energy locally heats the air and leads to a decrease in the air density which modifies the refractive index*
 - ii. Thermal blooming can be mitigated by path clearing, which can be achieved by vapourising the aerosol*

Turbulence Challenge

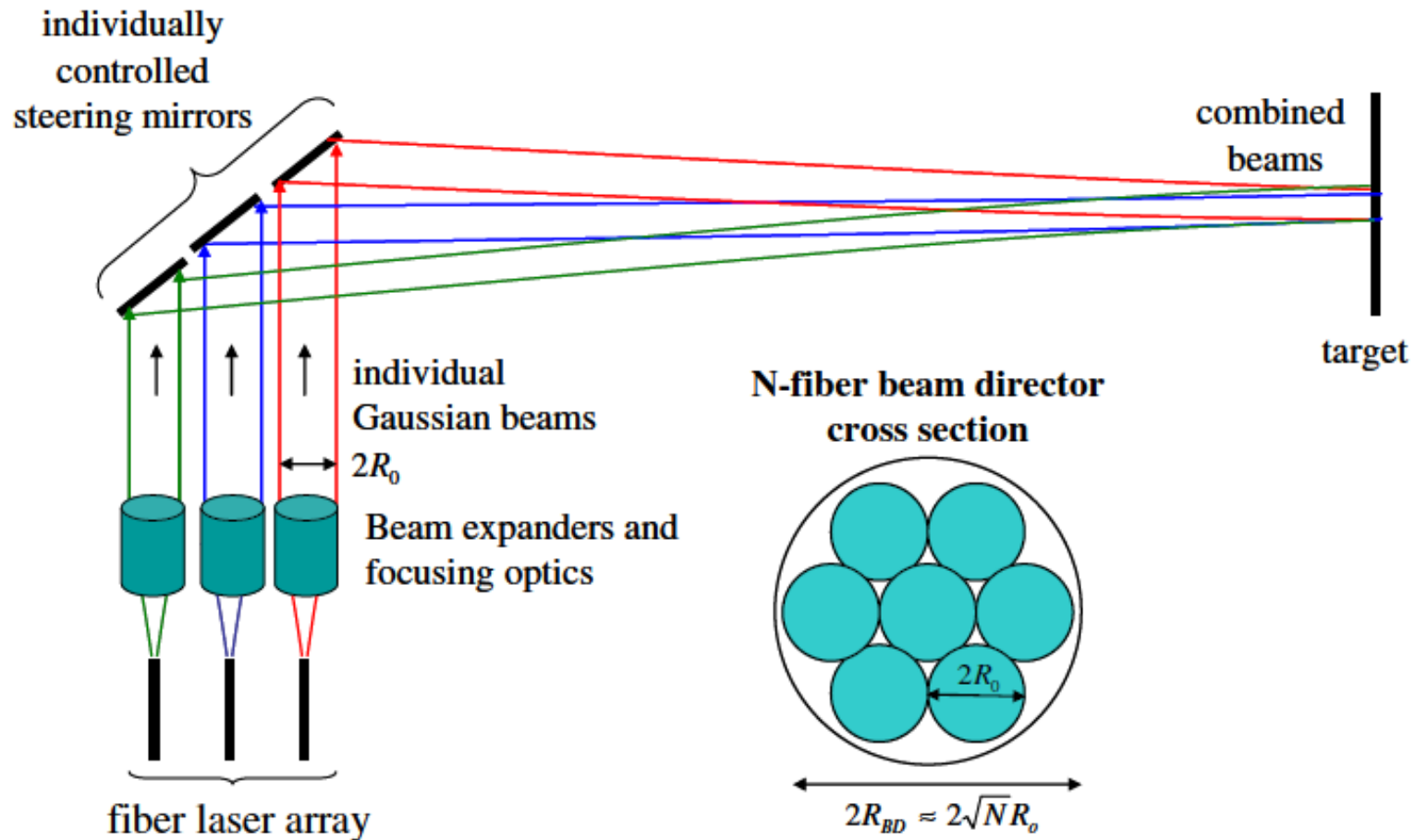
- Turbulence leads to spreading of the laser beam spot size R_s and wandering of the laser beam centroid R_w . The Figure^[2] shows the laser beam spot (dotted circles) at several instants in time.
- Adaptive optics can compensate for turbulence but not diffraction or poor beam quality.
- R_w is the centroid displacement (wander), and R_s is the increase in spot size (spreading)
- $R = (R_w^2 + R_s^2)^{1/2}$



- Limit diffractive spreading over the range
- The individual spot sizes (radius) of the beams must be large enough at the source and have good optical quality. $R_o \geq 10 \text{ cm}$

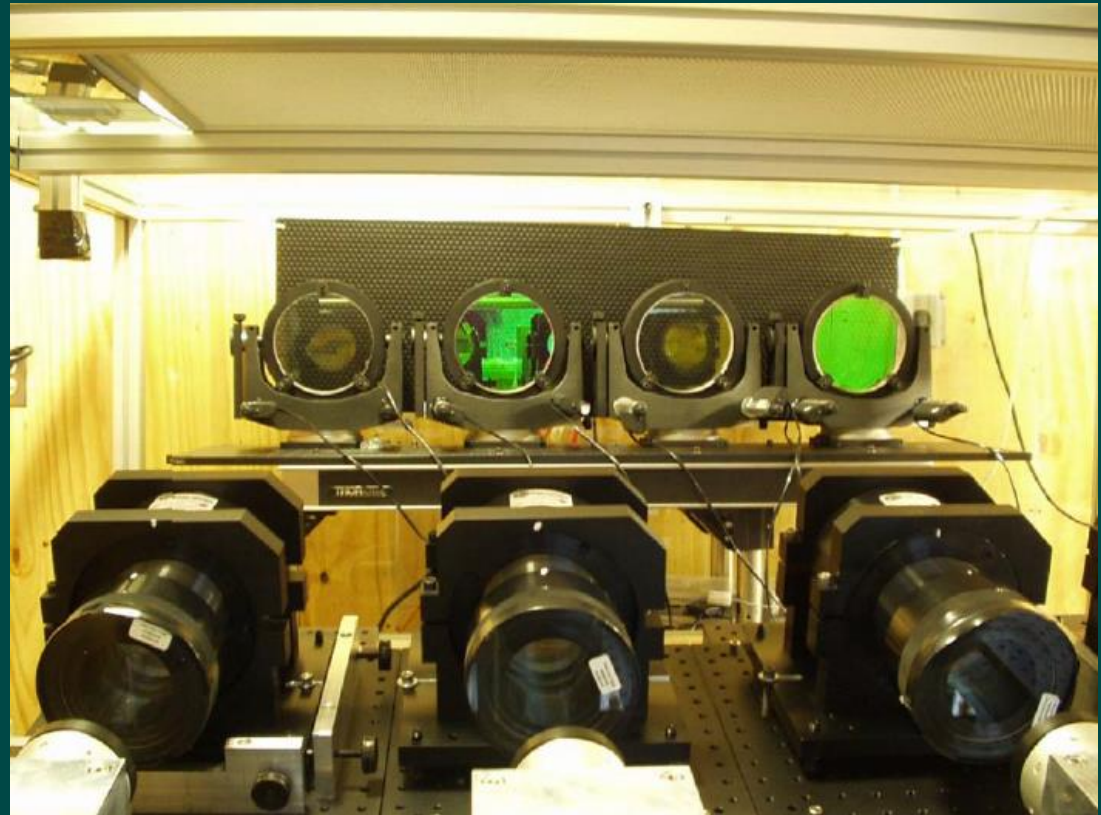
- Coherent combining would require a narrow spectral linewidth, phase locking, as well as polarisation alignment of all the lasers.
- These are very difficult requirement for high power lasers and in the presence of moderate turbulence the benefits of coherent combining are lost.
- Incoherent combining is much more practical
- Its range can be extended using adaptive optics

Incoherently combined fiber lasers individually directed to the target.



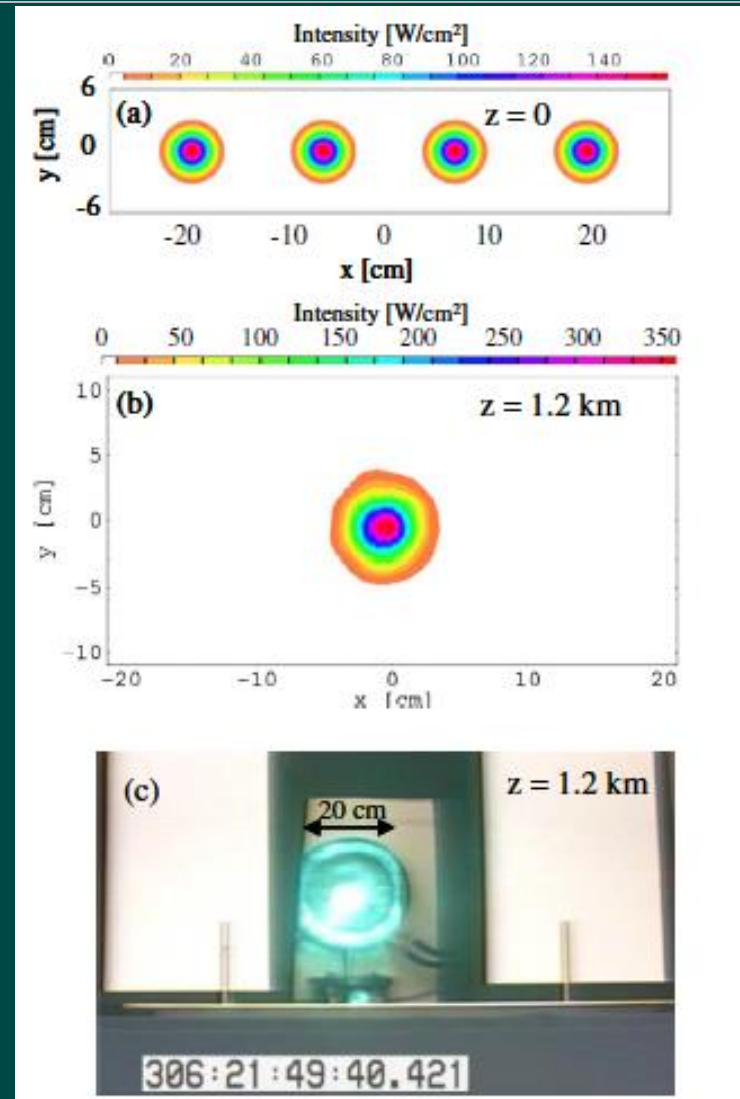
NRL beam director used for incoherent combining

- Three of four fiber laser collimators and beam expanders are shown in the foreground.^[2]
- Four individually controlled steering mirrors are shown in the background.



Incoherent beam combining

- Simulation showing a 2 s time-averaged transverse intensity profile of laser beams at [2]
- (a) the source and
- (b) incoherently combined on a target at a range of 1.2 km for a turbulence strength of $C_n^2 = 5 \times 10^{-14} \text{ m}^{-2/3}$, wind speed of 2.5 m/s, aerosol scattering coefficient of 0.05 km^{-1} , and mechanical jitter of $1\text{--}2 \text{ }\mu\text{m}$. The individual initial spot size is $\sim 2.5 \text{ cm}$ and the combined spot size on target is $\sim 3\text{--}4 \text{ cm}$.
- (c) CCD camera image of four beams incoherently combined on target (20 cm diameter power meter) at a range of 1.2 km. The total transmitted power was 3 kW and the propagation efficiency $\sim 90\%$ in the experiment.





Success in targeting drones



Lockheed Martin 30 kW system using Spectral beam combining



Lockheed Martin 30 kW

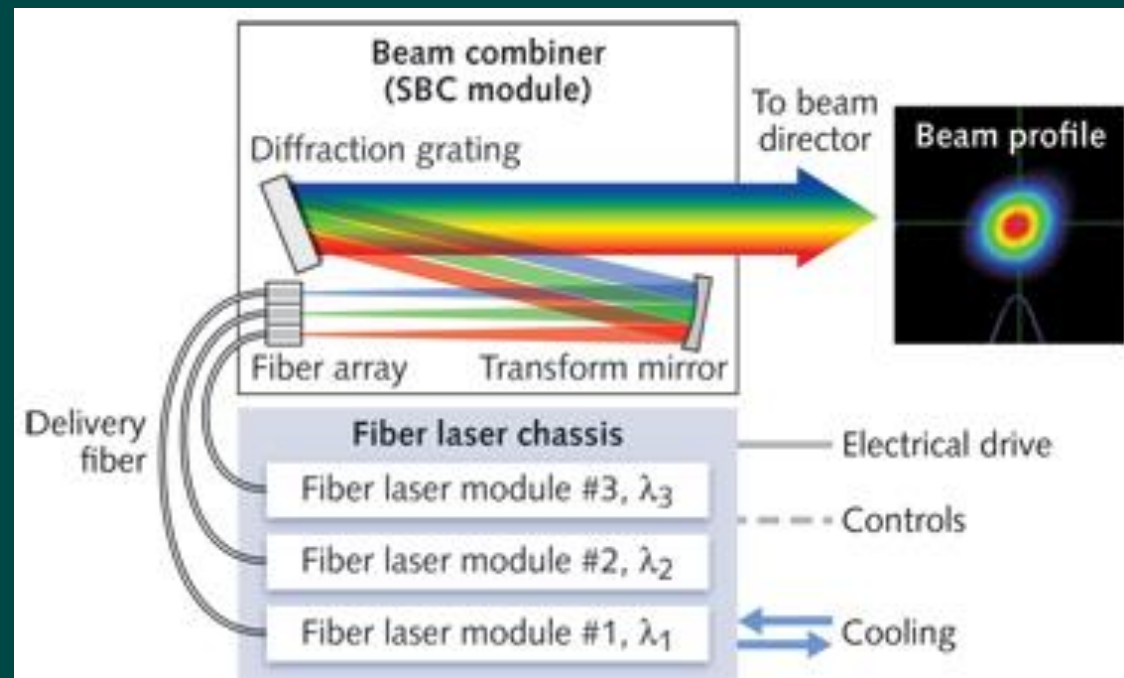
BETHESDA, Md., March 3, 2015 – Lockheed Martin's [NYSE: LMT] 30-kW fiber laser system successfully disabled the engine of a small truck during a recent field test, demonstrating the rapidly evolving precision capability to protect military forces and critical infrastructure.

<http://www.sme.org/MEMagazine/Article.aspx?id=84571&taxid=3440#sthash.gn1DnEoL.dpuf>



Spectral Beam Combining

- The unique process, called Spectral Beam Combining, sends beams from multiple fibre laser modules, each with a unique wavelength, into a combiner that forms a single, powerful, high quality beam.



Lockheed Martin demonstrate 30kW Laser

- The 30-kilowatt beam combines many fibre lasers operating a slightly different wavelengths into a single "near perfect" band of light.
- Lockheed says the upgraded system produced the highest power ever documented while still retaining beam quality and electrical efficiency and using 50% less electrical power than solid-state lasers.



- If the US Government had been shown the beam divergence equation: $\theta = M^2 \lambda / \pi \omega_0$, they could have saved \$5 billion.
- In general, what does this say about technical review processes?
- The current short range fibre laser based systems are increasingly effective and realistic.
- Fibre laser based systems do not have the complex logistical problems that the COIL laser creates.
- Its all about watts/m²

- 1) ["BBC NEWS – Science/Nature – 'Laser jumbo' testing moves ahead". bbc.co.uk.](http://bbc.co.uk)
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